Reducing Environmental Impacts: Coal Combustion

Case Study

A Life Cycle Comparison of Disposal and Beneficial Use of Coal Combustion Products in Florida

Part 1: Methodology and Inventory of Materials, Energy, and Emissions*

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Abstract

Background, Goal, and Scope. Currently, only 40%, or 44.5 million metric tons, of coal combustion products (CCPs) generated in the United States each year by electric utilities are diverted from disposal in landfills or surface impoundments and recycled. Despite promising economic and environmental savings, there has been scant attention devoted to assessing life cycle impacts of CCP disposal and beneficial use. The objective of this paper is to present a life cycle inventory considering two cases of CCP management, including the stages of coal mining and preparation, coal combustion, CCP disposal, and CCP beneficial use. Six beneficial uses were considered: concrete production, structural fills, soil amendments, road construction, blasting grit and roofing granules, and wallboard.

Methods. Primary data for raw material inputs and emissions of all stages considered were obtained from surveys and site visits of coal-burning utilities in Florida conducted in 2002, and secondary data were obtained from various published sources and from databases available in SimaPro 5.1 (PRé Consultants, Amersfoort, The Netherlands).

Results. Results revealed that 50 percent of all CCPs produced, or 108 kg per 1,000 kg of coal combusted, are diverted for application in a beneficial use; however, the relative amounts sold by each utility is dependent on the process operating parameters, air emission control devices, and resulting quality of CCP. Diversion of 50% of all CCPs to beneficial use applications yields a decrease in the total raw materials requirements (with the exception of gravel and iron) and most emissions to air, water, and land, as compared to 100% disposal.

Discussion. The greatest reduction of raw materials was attributed to replacing Portland cement with fly ash, using bottom ash as an aggregate in concrete production and road construction in place of natural materials, and substituting FGD gypsum for natural gypsum in wallboard. The use of fly ash as cementitious material in concrete also promised significant reductions in emissions, particularly the carbon dioxide that would be generated from Portland cement production. Beneficial uses of fly ash and gypsum showed reductions of emissions to water (particularly total dissolved solids) and emissions of metals to land, although these reductions were small compared to simply diverting 50% of all CCPs from landfills or surface impoundments.

Conclusions. This life cycle inventory (LCI) provides the foundation for assessing the impacts of CCP disposal and beneficial use. Beneficial use of CCPs is shown here to yield reductions in raw material requirements and various emissions to all environmental compartments, with potential tangible savings to human health and the environment.

Recommendations and Perspectives. Extension of this life cycle inventory to include impact assessment and sensitivity analysis will enable a determination of whether the savings in emissions reported here actually result in significant improvements in environmental and human health impacts.

Keywords: Coal combustion, beneficial use; coal combustion products (CCPs); disposal; emissions, coal combustion; Florida; Life Cycle Inventory (LCI)

Introduction

Approximately 110 million metric tons of coal combustion products (CCPs), categorized as fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) material, are generated annually by electric utilities in the United States [1]. Fly ash is the ash and non-combustible minerals released during combustion that 'fly' out of the boiler with flue gases [2]. Bottom ash and boiler slag are heavy, non-combustible particles remaining in the bottom of the boilers [3]. FGD material is the residue of air emissions control devices that remove sulfur dioxide (SO_2) from the flue gas. The physical and chemical characteristics of CCPs enable their use in engineering and manufacturing markets, and, as a result, CCPs have become the third most abundant mineral resource in the United States [6]. It is estimated that 44.5 million metric tons, or 40 percent, of CCPs generated in the United States are diverted to beneficial uses, i.e., the replacement of virgin raw materials by CCPs in industrial applications. Examples of the most promising beneficial uses include substitution of fly ash for Portland cement in concrete production [4,6–9], bottom ash as lightweight aggregate, in structural fill, and in road bases and sub-bases [4,6,10–14], FGD gypsum for natural gypsum in wallboard manufacture [15–17], and boiler slag in blasting grit and asphalt roofing granules [6,18,19]. CCPs are also used as agricultural soil amendments and in material recovery and waste stabilization [1].

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The remaining 60 percent of CCPs generated are disposed of in landfills or surface impoundments located at the electric utility [1, 20]. Both disposal methods risk release of trace metals to the water and land and require burdensome permitting and extensive land mass [21]. A recent life cycle inventory (LCI) of coal used for electricity production in Florida reported that, for every 1000 kg of coal combusted, 216 kg of CCPs are produced, including fly ash (80 kg), bottom ash (9 kg), boiler slag (7 kg), and FGD gypsum (120 kg) [20]. This study identified CCP beneficial use as an opportunity to prevent or minimize emissions and potential environmental impacts resulting from CCP disposal [20]. Other benefits from CCP beneficial use may include decreased reliance on scarce and/or expensive natural resources, decreased energy requirements for processing or transporting the CCPs for disposal, and increased financial returns to the utilities and intermediate marketers from CCPs sales.

Most research on the potential environmental impacts of CCPs has centered on the effect that metals released from landfills or surface impoundments may have on human and ecosystem health [22–24]. A recent study addressed coal byproducts from a life cycle perspective, but limited the analysis of CCPs to substitution of fly ash and bottom ash for cement in concrete and did not explicitly compare disposal and other beneficial use options [25]. Environmental and human health impacts resulting from diverting CCPs from disposal and replacing virgin raw materials are not well understood. To this end, the broad objective of this work was to use life cycle assessment (LCA) methods to expand the results of an LCI that focused on cradle-to-grave stages of coal used for electricity production in Florida by including CCP beneficial use. Here, Part 1 focuses on the LCI methodology and the comparative inventory of raw materials and emissions for beneficial use and disposal of CCPs in Florida. Whether these emission reductions result in significant improvements in environmental and human health impacts will be the focus of Part 2 of this series.

1 Methods

This LCA was performed following ISO 14040 series guidelines [26a–c]. Inventory calculations for Part 1 were based on primary data (collected directly from Florida utilities) and secondary data (collected from literature and regulatory agencies), and performed with SimaPro 5.1 (PRé Consultants, Amersfoort, The Netherlands). SimaPro 5.1 also contains inventory data for products and processes in databases created by ETH-ESU (Uster, Switzerland), Buwal 250 (Bern, Switzerland), and Franklin Associates (Prairie Village, Kansas, USA), among others [27].

1.1 Goal definition and scope of this study

The primary goals of this LCI were to inventory raw material requirements and pollutant emissions associated with common CCP beneficial uses and use these results to determine opportunities in the CCP life cycle for preventing or minimizing environmental or human health impacts. The ultimate objective was to aid regulators and CCPs generators in determining methods of CCP management that result in minimal impact to human and environmental health. The LCI scope included coal mining and preparation, coal combustion, CCP disposal, and CCP beneficial use. This assessment was limited to electric utilities during 2002 in the state of Florida, as this project was funded by the Florida Department of Environmental Protection (FDEP) and involved collaboration with the Florida Electric Power Coordinating Group (FCG), a consortium of electric utilities in Florida. Furthermore, this LCI specifically included coal processing and combustion technology that is currently used and well established. As shown in **Fig. 1**, two scenarios were considered: the baseline coal life cycle with 100% CCP disposal in onsite landfills and surface impoundments (**Fig. 1A**) and the CCP beneficial use scenario, with 50% of all CCPs diverted from disposal and used as raw material replacements in beneficial uses within 50 miles of the utility (**Fig. 1B**).

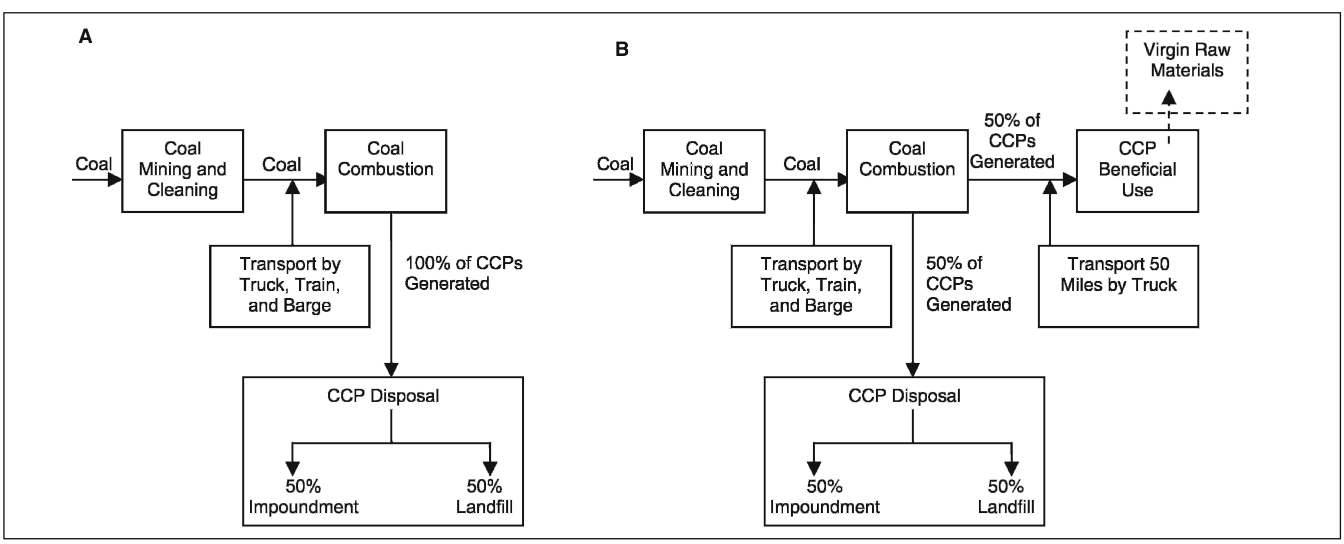

Fig. 1: Life cycle system boundaries. A: Baseline scenario – coal combustion with 100% CCP disposal. B: Baseline scenario – coal combustion with 50% CCP disposal and 50% CCP beneficial use within 50 miles

Since the CCP beneficial use stage involves substitution of CCPs for other materials, the system included upstream processes for materials replaced by CCPs, since CCPs have similar characteristics and performance as the materials they replace [28]. However, the use, recycling, and disposal of products made from beneficial use applications were not considered, as it was assumed that these would be unchanged by use of CCPs. This assumption neglects impacts that could be created by use of CCPs over the lifetime of the products in which they are used, for example, impacts caused by the release of trace elements contained in the CCPs into surrounding ecosystems where the product is used. This assumption was, however, necessitated by a lack of available data regarding regional and temporal performance and environmental impacts of products made with CCPs.

1.1.1 Functional unit

Despite the common use of 'per kWhr of energy generated' in LCAs involving energy production [29–34], the functional unit used for this study was 'per 1000 kg of coal combusted.' Applying a mass basis affords better clarity and comparability of the results, given that most inputs and outputs of this system are reported by mass. This unit also allows for scaling of results over any time period of interest, provided that the technology and process parameters are comparable to those included in this study. However, using a mass-based functional unit does not exclude comparison by power generated or units specific to a given power plant or region of interest if the coal's heating value and the power plant's efficiency and operating capacity are known.

1.1.2 System boundaries

The system in consideration in this study represents typical processes at pulverized coal-fired power generation sites in Florida, although these processes are common to power plants across the U.S. [29–33]. Boundaries for each stages (see Figs. 1A and B) included extraction and preparation of natural resources, production of materials and chemicals, transportation, construction of necessary capital goods and infrastructure, energy consumption, and emissions to air, water, and land. The system included transportation of the CCPs from the utility to their final beneficial use, assuming an average transportation distance of 50 miles from the utility, reported by surveyed utilities to be a distance beyond which transportation costs could be prohibitive. Based on a previous LCI that focused on coal used by electric utilities in Florida [20] and results described in Section 2.1 to follow, an assumption was made that 50 percent (108 kg) of CCPs generated from combusting 1000 kg of coal is equally divided for disposal in a landfill or surface impoundment and the remaining 50 percent (108 kg) is diverted to a beneficial application as a replacement for virgin raw material. **Table 1** lists beneficial uses for each CCP type in this LCA and the relative percentages used in each application, as reported by the utilities surveyed in this study and national coal combustion market reports [1,4,6].

Specific sub-stages for virgin raw materials included in the expanded scope involved mining, processing, and transportation of the traditionally used materials. It was assumed that, for every mass unit of CCP used in a beneficial application stated above, the traditional raw material required would be decreased by the same amount. Fly ash replaced Portland cement in concrete; all CCPs replaced sand and gravel in structural fills; fly ash and FGD material replaced fertilizers and commercial additives in soil amendments; fly ash and bottom ash replaced paving, base, and sub-base materials in road construction; boiler slag replaced sand, gravel, and quartz in blasting grit and roofing granules; and FGD gypsum replaced natural gypsum in wallboard. This approach was used because of the ability to embed 'avoided processes' in the calculations of raw material use and emissions from actual processes, as performed using the SimaPro 5.1 software.

1.2 Inventory of material and energy inputs and outputs

This life cycle inventory (LCI) focused on comparative stages of 50% CCP disposal and 50% CCP beneficial use, extending a previous inventory on coal mining and cleaning, coal combustion, and 100% CCP disposal [20] (see Fig. 1A). A discussion of methods used for data collection, verification of data quality, addressing data limitations, and allocation is provided below.

1.2.1 Data collection

Data were collected, in part, from interviews and site visits at four utilities, chosen by the FCG as representative of the coal-fired utilities in Florida, and surveys sent to CCP marketers and environmental managers at other utilities in Florida. Some of the representative characteristics of the four visited utilities, labeled as Sites 1–4, respectively, have been previously presented [20]. Information collected for this study included types of CCPs produced, their quality, and quantities sold for beneficial use. Data were also obtained from monitoring and compliance reports and databases published by the U.S. Environmental Protection Agency (U.S. EPA), including hourly air emissions from the Acid Rain/Ozone Transport Commission and Toxics Release Inventory (TRI)

Table 1: Beneficial use applications of CCPs and average relative percentages used in each by the Florida utilities and considered in this study

Fly Ash and Bottom Ash		Boiler Slag		FGD Material	
Beneficial Use	Percentage	Beneficial Use	Percentage	Beneficial Use	Percentage
Cement and concrete production	70%	Roofing granules and blasting grit	98%	Gypsum wallboard	90%
Structural fill	20%	Structural fill	1%	Soil amendment	8%
Road base and subbase	10%	Mineral filler	1%	Cement and concrete production	2%

reports of the participating utilities [35–36]. Other secondary data sources included published literature and reports from the American Coal Ash Association (ACAA) and the Electric Power Research Institute (EPRI). Where no other data were available, databases by ETH-ESU (Uster, Switzerland) and Franklin Associates (Prairie Village, Kansas, USA), included in SimaPro 5.1, were used, providing they met the data quality requirements detailed below [27].

1.2.2 Data quality

Use of data from such a variety of primary and secondary sources is accompanied by concerns over the inability to verify data collection and verification methods followed by each source. In this study, the uncertainty arising from this lack of consistency was minimized by using three qualitative uncertainty criteria [37] and using only reasonable data that met these criteria. First, data had to be dated 1990 to present for processes using average, modern, or best available technology. Second, data from the U.S. were preferred. European data provided in the ETH-ESU database were included if they were the only information available and consistent in scope and magnitude of U.S. data from similar processes. Third, data were obtained only for a specific process included in the LCA or from an average of all processes with the same function or product.

1.2.3 Data limitations

In this study, despite a significant amount of information provided directly from the utilities, uncertainty stems from using data that originate from different sources and that are specific to Florida utility operations. Although this places a geographic limitation on the widespread use of results and conclusions of this LCA, the technology and operational practices modeled herein for coal combustion and CCP beneficial use are common across the electric utility industry in the U.S. [29–33], and, therefore, results of this study can be applied with caution to other regions of the U.S. Furthermore, sensitivity analysis, detailed in Part 2 of this paper, was used to determine the effect of variability of selected system parameters on study outcomes.

1.2.4 Allocation

In the coal combustion stage, material and energy requirements for coal combustion and resulting emissions to the environment were allocated between electricity generation and CCP generation. This shared process was allocated by classifying the CCPs as waste products from a system that is designed and optimized for electricity generation and expanding the system to include downstream management of CCPs by disposal in landfills or surface impoundments or by beneficial use. Allocation in the CCP disposal stage was addressed by partitioning each process specific to each of the CCPs generated, for example, allocating all emissions and impacts specific to the landfilling of fly ash to the relative mass of fly ash produced. This approach is possible since each of the disposal methods has a single function and separate available environmental data [28]. In the case of CCPs that are diverted to beneficial use applications, as previously described, allocation has been largely avoided by expanding the boundaries of the system to include the upstream life cycles of materials replaced by CCPs in beneficial use applications.

2 Results and Discussion

2.1 Survey data specific to Florida utilities

As described in Section 1.1.2, 50% of CCPs produced in Florida, or 108 kg per 1000 kg of coal combusted, are diverted to a beneficial use. The relative amounts of CCPs produced and sold by the four representative utilities that were visited in 2002, Sites 1–4, were dependent on process operating parameters, air emission control devices used, and CCP quality. For example, unlike Sites 1 and 4, Sites 2 and 3 require FGD systems, and, therefore, generate FGD byproduct that contains sulfur products originating from the source coal and the non-regenerable sorbent injected for SO_2 removal. Sites 1, 2, and 4 sold some or all of each type of CCP for a beneficial application, based on favorable demand. Site 1 generated 145,000 metric tons/year of fly ash and bottom ash, and sold 74% of these products for concrete production. Site 2 generated 1.09 million metric tons/year of fly ash, bottom ash, boiler slag, and FGD gypsum and sold 99% of these CCPs for use in concrete production, blasting grit, roofing granules, gypsum wallboard production, and land applications. Site 4 produced only fly ash and bottom ash (508,000 metric tons/year) and sold 90% of this material for production of lightweight aggregate and concrete. Site 3 produced nearly 227,000 metric tons of fly ash, bottom ash, and FGD material in 2002, but none of these CCPs were used. These products possessed variable physical and chemical characteristics because the Site 3 uses co-combustion of coal with municipal solid waste (MSW). As a result, the CCPs are not marketable for beneficial use and are combined and disposed on site

2.2 Data inventory results

Over 500 inputs and outputs were tracked in the CCP life cycle; however, only materials contributing the highest 99.9% by mass (a total of 45 inputs and emissions) were presented in the final inventory. However, no material input or output was eliminated when performing subsequent impact assessment (Part 2). Inventory results for raw material and energy inputs to the beneficial use and disposal stages per 1000 kg coal combusted are provided in **Table 2**. Emissions to air, water, and land from these stages per 1000 kg coal combusted are provided in **Tables 3A–3C**. These tables summarize the inventory for each type of CCP used and for disposal of all CCPs by landfill or surface impoundment. Complete inventory tables that detail the inputs and emissions for each specific beneficial use are provided in **Tables 4 and 5** as an **Appendix** to this paper. In many cases, the inventory results are negative, indicating that an input or emission is prevented by the use of a CCP in place of a virgin raw material in the beneficial use. Inventory results for the stages of coal mining and preparation and coal combustion, not shown here, have been presented previously [20] and are unchanged for this assessment.

Table 2: Raw materials required for CCP beneficial use and disposal per 1,000 kg coal combusted

		Beneficial Use (50% of CCPs)					Disposal (50% of CCPs)			Total
Substance	**Unit**	**Boiler Slag**	**FGD Material**	**Fly Ash/ Bottom Ash**	**Transport 50 miles**	**Beneficial Use Total**	**Impoundment**	**Landfill**	**Disposal Total**	**Beneficial Use + Disposal**
Gravel	kg	–1.0	–0.5	–8.5	1.7	**–8.3**	40	43	**83.0**	**75**
Limestone	kg	–0.048	–7.3	–36	0.060	**–44**	0.046	0.76	**0.81**	**–43**
Coal	kg	–0.057	–1.8	–5.3	0.15	**–6.9**	0.30	0.42	**0.72**	**–6.2**
Iron	kg	–2.8E-04	–0.30	–0.035	0.052	**–0.28**	0.18	0.18	**0.36**	**0.077**
Clay	kg	–0.021	–0.34	–13	0.011	**–14**	0.0049	0.18	**0.18**	**–13**
Gypsum	kg	–6.4E-04	–62.2	–1.8	0.0022	**–64**	0.0010	0.037	**0.038**	**–64**
Sand	kg	–1.7	–0.040	–0.0042	0.0013	**–1.8**	0.0031	0.0032	**0.0063**	**–1.8**
Baryte	kg	–2.2E-05	–0.015	–0.0015	0.0011	**–0.015**	0.0033	0.0034	**0.0067**	**–0.009**
Bentonite	kg	–4.3E-06	–0.0039	–4.4E-04	5.6E-04	**–0.0038**	0.0019	0.0019	**0.0038**	**1.5E-05**
Methane	kg	–1.1E-04	–0.006	–0.011	4.4E–04	**–0.016**	0.0014	0.0016	**0.0030**	**–0.013**
Water	m^3	–0.013	–1.7	–0.21	0.027	**–1.9**	0.44	0.029	**0.47**	**–1.5**
Crude Oil	m^3	–4.4E-04	–0.23	–0.027	0.022	**–0.24**	0.070	0.071	**0.14**	**–0.10**
Natural Gas	m^3	–0.0024	–1.3	–0.12	0.0064	**–1.4**	0.0086	0.011	**0.020**	**–1.4**

Negative values indicate that replacement of a material by the CCP eliminated a virgin raw material requirement in the upstream LCI.
Materials shown represent the greatest 99.9% of all raw materials required by mass

Table 3A: Inventory of emissions to air (kg) for CCP beneficial use scenario: 50% disposal of CCPs and 50% beneficial use of CCPs within a 50-mile radius, per 1,000 kg coal combusted

	Beneficial Use (50% of CCPs)					Disposal (50% of CCPs)			Total
	Boiler Slag	**FGD Material**	**Fly Ash/ Bottom Ash**	**Transport 50 miles**	**Beneficial Use Total**	**Impoundment**	**Landfill**	**Disposal Total**	**Beneficial Use + Disposal**
Carbon Dioxide (CO_2)	–0.44	–24	–32	1.8	**–55**	2.4	3.2	**5.6**	**–49**
Particulate Matter (PM_{10})	–3.6E-04	–0.15	–0.024	0.0018	**–0.18**	1.1	1.1	**2.1**	**1.9**
Nitrogen Oxides (NO_x)	–0.0035	–0.19	–0.078	0.018	**–0.25**	0.017	0.020	**0.037**	**–0.21**
NonMethane Volatile Organic Compounds (NMVOC)	–0.0011	–0.059	–0.010	0.0069	**–0.063**	0.015	0.015	**0.030**	**–0.033**
Carbon Monoxide (CO)	–0.0035	–0.067	–0.040	0.0054	**–0.11**	0.0092	0.010	**0.019**	**–0.086**
Sulfur Dioxide (SO_2)	–0.0042	–0.074	–0.056	0.0050	**–0.13**	0.0088	0.010	**0.019**	**–0.11**
Methane (CH_4)	–8.6E-04	–0.35	–0.028	0.0027	**–0.38**	0.0072	0.0078	**0.015**	**–0.36**

Negative values indicate that replacement of a material by the CCP eliminated an emission to air from virgin raw material production in the upstream LCI.
Materials shown represent the greatest 99.9% of all emissions to air by mass

Table 3B: Inventory emissions to water (kg) for CCP beneficial use scenario: 50% disposal of CCPs and 50% beneficial use of CCPs within a 50-mile radius, per 1,000 kg coal combusted

	Beneficial Use (50% of CCPs)					Disposal (50% of CCPs)			Total
	Boiler Slag	**FGD Material**	**Fly Ash and Bottom Ash**	**Transport 50 miles**	**Beneficial Use Total**	**Impoundment**	**Landfill**	**Disposal Total**	**Beneficial Use + Disposal**
Total Dissolved Solids (TDS)	–0.0053	–0.30	–0.11	0.050	**–0.36**	17	0.28	**17.5**	**17.2**
Iron (Fe)	–1.2E-05	–7.8E-04	–0.0021	4.5E-05	**–0.0029**	0.023	0.0051	**0.028**	**0.025**
Barium (Ba)	–2.9E-06	–7.1E-04	–6.1E-04	7.5E-05	**–0.0013**	0.026	3.88E-04	**0.027**	**0.025**
Potassium (K)	–8.7E-06	–0.0016	–0.0021	1.6E-04	**–0.0036**	0.010	0.0055	**0.015**	**0.012**
Total Suspended Solids (TSS)	–2.2E-04	–0.015	–0.0036	0.0017	**–0.017**	0.0049	0.0050	**0.010**	**–0.0076**
Nitrogen (Total N)	–2.1E-06	–9.9E-04	–9.6E-05	9.8E-05	**–9.9E-04**	0.0061	0.0034	**0.0095**	**0.0085**
Total Organic Carbon (TOC)	–1.0E-05	–0.0053	–0.0012	0.0048	**–0.0018**	0.0033	0.0035	**0.0069**	**0.0051**
Boron (B)	–5.3E-06	–1.0E-04	–9.3E-05	9.8E-06	**–1.9E-04**	0.0044	0.0022	**0.0067**	**0.0065**
Silica (Si)	–4.4E-10	–1.9E-05	–6.1E-08	4.4E-09	**–1.9E-05**	0.0041	0.0021	**0.0062**	**0.0062**
Aluminum (Al)	–2.1E-05	–0.0016	–0.0066	8.8E-05	**–0.0081**	0.0033	0.0020	**0.0054**	**–0.0028**
Magnesium (Mg)	–1.8E-05	–0.0016	–0.0054	1.1E-04	**–0.0069**	0.0037	6.06E-04	**0.0043**	**–0.0026**

Negative values indicate that replacement of a material by the CCP eliminated an emission to water from virgin raw material production in the upstream LCI.
Materials shown represent the greatest 99.9% of all emissions to water by mass

Table 3C: Inventory of emissions to land (kg) for CCP beneficial use scenario: 50% disposal of CCPs and 50% beneficial use of CCPs within a 50-mile radius, per 1,000 kg coal combusted

	Beneficial Use (50% of CCPs)					Disposal (50% of CCPs)			Total
	Boiler Slag	FGD Material	Fly Ash and Bottom Ash	Transport 50 miles	Beneficial Use Total	Impoundment	Landfill	Disposal Total	Beneficial Use + Disposal
Barium (Ba)	–4.1E-07	–0.0023	–9.7E-05	1.6E-05	**–0.002**	2.4E-05	8.6	**8.6**	**8.6**
Copper (Cu)	–2.5E-07	–0.0014	–5.9E-05	1.0E-05	**–0.001**	1.5E-05	5.3	**5.3**	**5.3**
Manganese (Mn)	–8.2E-08	–4.6E-04	–1.9E-05	3.2E-06	**–0.0005**	4.8E-06	1.7	**1.7**	**1.7**
Zinc (Zn)	–7.1E-08	–4.0E-04	–1.7E-05	2.9E-06	**–0.0004**	4.3E-06	1.5	**1.5**	**1.5**
Chromium (Cr)	–4.3E-08	–2.5E-04	–1.0E-05	1.7E-06	**–0.0003**	2.6E-06	0.92	**0.92**	**0.92**
Nickel (Ni)	–3.0E-08	–1.7E-04	–7.0E-06	1.2E-06	**–0.0002**	1.8E-06	0.63	**0.63**	**0.63**
Arsenic (As)	–2.8E-08	–1.6E-04	–6.7E-06	1.1E-06	**–0.0002**	1.7E-06	0.60	**0.60**	**0.60**
Lead (Pb)	–2.4E-08	–1.3E-04	–5.6E-06	9.5E-07	**–0.0001**	1.4E-06	0.50	**0.50**	**0.49**
Vanadium (V)	–1.3E-08	–7.6E-05	–3.2E-06	5.4E-07	**–0.0001**	7.9E-07	0.28	**0.28**	**0.28**
Cobalt (Co)	–3.5E-09	–2.0E-05	–8.4E-07	1.4E-07	**–2.1E-05**	2.1E-07	0.075	**0.075**	**0.075**
Mercury (Hg)	–3.1E-10	–1.7E-06	–7.2E-08	1.2E-08	**–1.8E-06**	1.8E-08	0.0065	**0.0065**	**0.0065**
Molybdenum (Mo)	–2.0E-10	–1.1E-06	–4.7E-08	7.9E-09	**–1.2E-06**	1.2E-08	0.0042	**0.0042**	**0.0042**
Beryllium (Be)	–4.5E-11	–2.6E-07	–1.1E-08	1.8E-09	**–2.6E-07**	2.7E-09	9.52E-04	**9.52E-04**	**9.52E-04**

Negative values indicate that elimination of an emission by the CCP eliminated an emission to land from virgin raw material production in the upstream LCI.Materials shown represent the greatest 99.9% of all emissions to land by mass

2.2.1 Inventory of material and energy inputs

As shown in Table 2, when 50% of the CCPs produced are divided equally between disposal and beneficial use, the disposal stage require inputs of all raw materials included in the inventory. Construction and operation of CCP disposal facilities requires a large amount of gravel and smaller amounts of other materials. Transportation of CCPs 50 miles to their beneficial use market also represents a net requirement of raw material and energy inputs, attributed to equipment, infrastructure and fuel.

On the other hand, some raw material requirements are reduced when half of the produced CCPs are diverted to beneficial use applications. Clay (–14 kg) and gravel (–9.2 kg) are replaced by CCPs in structural and flowable fill and road base and sub-base applications, thus resulting in net reduction of raw material requirements. Other significant reductions are shown for the replacement of FGD gypsum for natural gypsum (–62.2 kg) and fly ash for Portland cement. Crude oil, required for producing fuel oil used for electricity generation, mining equipment, and transportation vehicles, and methane, trapped in coal seams and eventually released when coal is mined, are prevented by CCP diversion to beneficial uses. Methane is considered an input here by the nature of the LCI boundaries and because it is a natural resource that could conceivably be used for alternative purposes if it were not released when the coal was mined. When summing the net raw material and energy requirements for CCP beneficial use and disposal, only two materials show a net positive value: gravel (73 kg) and iron (0.065 kg). Although these materials are reduced by diversion of CCPs from disposal facilities and by substitution of CCPs for virgin raw materials, they were not avoided altogether because of the large quantities of gravel and iron used in construction and operation of the disposal infrastructure. Materials reduced by the highest total quantities per 1,000 kg of coal combusted were gypsum (–64 kg), limestone (–43 kg), and clay (–14 kg). Although these materials are not scarce or prohibitively expensive, their reduction still offers opportunities for environmental savings, particularly in the life cycle stages of raw material extraction and transportation. These savings may be less attractive, however, if the CCPs must be transported over distances longer than 50 miles from the utility.

2.2.2 Inventory of emissions

Tables 3A-3C show emissions to the environment from diverting 50% of CCPs produced from combustion of 1,000 kg of coal to CCP beneficial use applications and disposing of the remainder by traditional landfill and surface impoundment methods.

Considering releases to the air (see Table 3A), CCP beneficial use resulted in reduction of all emissions to varying degrees. CO_2 emissions, comprising 98% of air emissions by mass, are decreased in the greatest quantity, almost exclusively by replacement of fly ash for Portland cement in concrete production. Portland cement production in the U.S. yields high CO_2 emissions, up to 4.14×10^{10} kg per year in 2001 [38], and, therefore, the use of fly ash as a replacement raw material could potentially effect large CO_2 emission reductions. Other air emissions, including methane, sulfur dioxide, and nitrogen oxides, are reduced in smaller amounts by CCP beneficial use. CCP disposal accounts for only a small amount of emissions to air, primarily particulate matter (2.1 kg), which is generated by equipment used for CCP transportation and maintenance of the ash landfills as well as from fugitive dust emissions. Again, these savings would be drastically decreased if the transportation requirements were greater, since emissions of CO_2, NO_x, and PM_{10} would increase with any increase in vehicular transportation distance.

Considering emissions to water (see Table 3B), the beneficial use of CCPs by replacement of virgin raw materials yields reductions in all emissions considered. However, these reductions are small compared to the net emission to water from CCP disposal. The release of total dissolved solids (TDS) is reduced by 0.36 kg through beneficial use, but this reduction is only 2% of the total amount of TDS released

by CCP disposal, primarily resulting from the use of surface impoundments. There are net reductions of total suspended solids (–0.007 kg), aluminum (–0.0027 kg), and magnesium (–0.0026 kg) per 1,000 kg of coal combusted, associated with using fly ash and bottom ash in concrete production, structural fill, road base and subbase.

Savings from decreased landfill and surface impoundment disposal were also realized for all inventoried emissions to land (see Table 3C). These results are consistent with previous work that showed that CCP disposal accounts for almost all emissions to land and water accrued over the entire life cycle of coal used for electricity production [20]. Although the use of each CCP type in its beneficial use applications results in small reductions to metal emissions to land, these reductions are not significant compared to the total emissions still produced by CCP disposal. Considering emissions to land, the promise of reducing environmental impact is most related to the diversion of CCPs from disposal facilities, rather than replacement of virgin raw materials. However, the potential of reducing metal emissions would be diminished if the CCPs were used in applications where the metals can easily be released back into the environment, in which case the total emissions would only be removed in time and space from their original disposal point. This is primarily a concern for the use of CCPs in applications where they are applied directly to land with no modification, such as in soil amendment or road construction, rather than in applications where they are bound in a cementitious matrix, such as concrete production.

3 Conclusions

This life cycle inventory illustrates potential environmental benefit associated with diverting at least 50% of CCPs from disposal to beneficial uses in concrete, structural fill, soil amendment, road construction, blasting grit, roofing granules, and wallboard. When considering raw material and energy requirements and emissions to air, these advantages are due to the replacement of virgin raw materials by CCPs in their applications and in lesser part to the reduced operation and infrastructure of CCP disposal facilities. Raw material savings are particularly high where CCPs replace natural aggregate in structural fill or road base and subbase, natural gypsum in wallboard production, and Portland cement in concrete production. Reductions in air emissions are also significant when fly ash replaces Portland cement, due to the high quantities of CO_2 otherwise generated during Portland cement production. Emissions to water and land are reduced from the baseline scenario [20] simply because of diverting 50% of CCPs from landfills or impoundments. These emissions are slightly decreased by the actual use of CCPs, but by a much smaller degree than the emissions associated with disposal. All emissions would be expected to continue to decrease with increasing percentages of CCPs used in such construction and engineering applications as considered here. However, the environmental benefits from these uses may decrease if contaminants contained in the CCPs are released to the environment in which they are used or if the distance by which the CCPs must be transported to their beneficial use location increases.

Whether these emission reductions result in significant improvements in environmental and human health impacts will be the focus of Part 2 of this series. Impacts associated with all stages considered in the life cycle of CCPs, including CCP beneficial use, will be determined and compared across different impact assessment methods and beneficial use scenarios. Sensitivity analysis will be used to address variation in study results due to changing assumptions or process parameters.

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Appendix

Table 4: Complete inventory of raw material required

		Boiler Slag Beneficial Use			FGD Material Beneficial Use		
Substance	**Unit**	**Blasting Grit, Roofing Granules**	**Mineral Filler**	**Structural Fill**	**Cement**	**Gypsum**	**Soil Amendment**
Gravel	kg	–1.03E+00	–8.39E-04	–1.75E-02	–1.26E-02	–4.79E-01	–3.77E-02
Limestone	kg	–2.37E-03	–4.61E-02	–1.63E-06	–1.38E+00	–1.06E-01	–5.82E+00
Coal	kg	–4.04E-02	–1.66E-02	–2.30E-05	–1.99E-01	–1.02E+00	–5.41E-01
Iron	kg	–1.77E-04	–1.02E-04	–1.35E-06	–1.26E-03	–2.94E-01	–4.23E-03
Clay	kg	–6.37E-06	–3.11E-03	–1.75E-02	–3.36E-01	–5.77E-03	–4.51E-04
Gypsum	kg	–1.30E-06	–6.38E-04	–8.98E-09	–6.90E-02	–6.21E+01	–9.27E-05
Sand	kg	–1.72E+00	–6.28E-05	–8.27E-08	–1.57E-04	–3.47E-02	–5.09E-03
Baryte	kg	–1.24E-05	–9.41E-06	–8.56E-08	–5.56E-05	–1.43E-02	–3.52E-04
Bentonite	kg	–2.64E-06	–1.63E-06	–1.94E-08	–1.58E-05	–3.80E-03	–6.78E-05
Methane	kg	–1.45E-06	–1.08E-04	–1.10E-08	–4.10E-04	–2.69E-03	–2.83E-03
Water	m^3	–1.22E-02	–1.12E-03	–7.76E-05	–6.43E-03	–1.68E+00	–5.41E-02
Crude Oil	m^3	–3.04E-04	–1.36E-04	–1.85E-06	–1.01E-03	–2.35E-01	–1.55E-03
Natural Gas	m^3	–2.20E-04	–2.23E-03	–3.63E-07	–4.42E-03	–1.06E+00	–2.03E-01

		Fly Ash and Bottom Ash Beneficial Use			Transport	Total	Disposal (50% of CCPs Generated)		
Substance	**Unit**	**Cement**	**Road Base and Subbase**	**Structural Fill**	**Transport 50 miles**	**Beneficial Use Total**	**Impoundment**	**Landfill**	**Disposal Total**
Gravel	kg	–3.28E-01	–3.69E+00	–4.45E+00	1.66E+00	**–8.39E+00**	3.96E+01	4.26E+01	**8.22E+01**
Limestone	kg	–3.59E+01	–6.17E-01	–4.14E-04	6.02E-02	**–4.38E+01**	4.64E-02	7.61E-01	**8.07E-01**
Coal	kg	–5.17E+00	–9.91E-02	–5.84E-03	1.49E-01	**–6.94E+00**	3.04E-01	4.16E-01	**7.20E-01**
Iron	kg	–3.28E-02	–1.81E-03	–3.43E-04	5.15E-02	**–2.83E-01**	1.76E-01	1.75E-01	**3.51E-01**
Clay	kg	–8.73E+00	–1.50E-01	–4.45E+00	1.05E-02	**–1.37E+01**	4.94E-03	1.79E-01	**1.84E-01**
Gypsum	kg	–1.79E+00	–3.08E-02	–2.28E-06	2.15E-03	**–6.40E+01**	1.01E-03	3.67E-02	**3.77E-02**
Sand	kg	–4.08E-03	–1.07E-04	–2.10E-05	1.27E-03	**–1.76E+00**	3.08E-03	3.20E-03	**6.28E-03**
Baryte	kg	–1.44E-03	–5.60E-05	–2.18E-05	1.07E-03	**–1.52E-02**	3.32E-03	3.35E-03	**6.67E-03**
Bentonite	kg	–4.10E-04	–2.12E-05	–4.92E-06	5.59E-04	**–3.77E-03**	1.89E-03	1.89E-03	**3.78E-03**
Methane	kg	–1.06E-02	–1.93E-04	–2.79E-06	4.35E-04	**–1.64E-02**	1.41E-03	1.62E-03	**3.03E-03**
Water	m^3	–1.67E-01	–1.99E-02	–1.97E-02	2.67E-02	**–1.94E+00**	4.44E-01	2.90E-02	**4.73E-01**
Crude Oil	m^3	–2.63E-02	–1.13E-03	–4.70E-04	2.24E-02	**–2.43E-01**	7.00E-02	7.07E-02	**1.41E-01**
Natural Gas	m^3	–1.15E-01	–2.18E-03	–9.22E-05	6.40E-03	**–1.38E+00**	8.62E-03	1.15E-02	**2.01E-02**

Table 5A: Complete inventory of emissions to air

	Boiler Slag Beneficial Use			FGD Material Beneficial Use		
Emission (kg)	**Blasting Grit and Roofing Granules**	**Mineral Filler**	**Structural Fill**	**Cement**	**Gypsum**	**Soil Amendment**
Carbon Dioxide (CO_2)	–3.85-01	–5.08-02	–2.09-04	–1.20E+00	–1.88E+01	–4.45E+00
Particulate Matter (PM10)	–3.03-04	–5.68-05	–1.89-07	–8.87-04	–7.85-02	–7.38-02
Nitrogen Oxides (NO_x)	–3.41-03	–9.65-05	–1.06-06	–2.91-03	–1.78-01	–5.41-03
NonMethane Volatile Organic Compounds (NMVOC)	–1.05-03	–7.38-05	–4.87-07	–3.51-04	–5.81-02	–8.27-04
Carbon Monoxide (CO)	–8.23-04	–2.63-03	–3.60-07	–1.52-03	–6.38-02	–1.48-03
Sulfur Dioxide (SO_2)	–4.05-03	–1.90-04	–6.51-07	–2.10-03	–6.11-02	–1.03-02
Methane (CH_4)	–7.24-04	–1.34-04	–2.73-07	–1.04-03	–3.46-01	–4.24-03

	Fly Ash and Bottom Ash Beneficial Use			Transport	Total	Disposal (50% of CCPs Generated)		
Emission (kg)	**Cement**	**Road Base and Subbase**	**Structural Fill**	**Transport 50 miles**	**Beneficial Use Total**	**Impound–ment**	**Landfill**	**Disposal Total**
Carbon Dioxide (CO_2)	–3.12E+01	–6.08-01	–5.32-02	1.82E+00	**–5.49E+01**	2.40E+00	3.16E+00	**5.56E+00**
Particulate Matter (PM10)	–2.30-02	–4.66-04	–4.81-05	1.79-03	**–1.75-01**	1.05E+00	1.05E+00	**2.11E+00**
Nitrogen Oxides (NO_x)	–7.58-02	–1.75-03	–2.69-04	1.78-02	**–2.49-01**	1.72-02	2.02-02	**3.74-02**
NonMethane Volatile Organic Compounds (NMVOC)	–9.10-03	–3.51-04	–1.24-04	6.91-03	**–6.31-02**	1.47-02	1.52-02	**2.99-02**
Carbon Monoxide (CO)	–3.93-02	–8.17-04	–9.15-05	5.38-03	**–1.05-01**	9.15-03	1.03-02	**1.95-02**
Sulfur Dioxide (SO_2)	–5.46-02	–1.21-03	–1.65-04	5.01-03	**–1.29-01**	8.75-03	1.02-02	**1.89-02**
Methane (CH_4)	–2.69-02	–5.75-04	–6.95-05	2.65-03	**–3.77-01**	7.17-03	7.78-03	**1.50-02**

Negative values indicate that elimination of an emission by the CCP eliminated an emission from virgin raw material production in the upstream LCI. Materials shown represent the greatest 99.9% of all emissions to land by mass

Table 5B: Complete inventory of emissions to water

	Boiler Slag Beneficial Use			FGD Material Beneficial Use		
Emission (kg)	**Blasting Grit and Roofing Granules**	**Mineral Filler**	**Structural Fill**	**Cement**	**Gypsum**	**Soil Amendment**
Total Dissolved Solids (TDS)	–4.85-03	–4.61-04	–2.37-06	–3.93-03	–2.45-01	–5.35-02
Iron (Fe)	–5.59-06	–6.90-06	–3.93-09	–8.10-05	–4.21-04	–2.81-04
Barium (Ba)	–8.25-07	–2.09-06	–5.72-09	–2.30-05	–6.20-04	–7.10-05
Potassium (K)	–1.59-06	–7.10-06	–1.11-08	–8.10-05	–1.28-03	–2.87-04
Total Suspended Solids (TSS)	–2.02-04	–1.72-05	–1.55-07	–1.33-04	–1.46-02	–5.05-04
Nitrogen (Total N)	–1.12-06	–1.01-06	–7.88-09	–3.47-06	–8.78-04	–1.06-04
Total Organic Carbon (TOC)	–5.84-06	–4.42-06	–4.05-08	–4.17-05	–5.08-03	–2.03-04
Boron (B)	–4.96-06	–3.33-07	–2.08-09	–3.47-06	–7.34-05	–2.45-05
Silica (Si)	–1.14-11	–4.25-10	–8.55-14	–2.29-09	–9.15-07	–1.77-05
Aluminum (Al)	–2.82-07	–2.10-05	–2.13-09	–2.51-04	–5.29-04	–7.76-04
Magnesium (Mg)	–6.61-07	–1.71-05	–4.76-09	–2.03-04	–8.00-04	–6.18-04

Table 5B: Complete inventory of emissions to water (*cont'd*)

	Fly Ash and Bottom Ash Beneficial Use			Transport	Total	Disposal (50% of CCPs Generated)		
Emission (kg)	**Cement**	**Road Base and Subbase**	**Structural Fill**	**Transport 50 miles**	**Beneficial Use Total**	**Impound-ment**	**Landfill**	**Disposal Total**
Total Dissolved Solids (TDS)	–1.02-01	–3.05-03	–6.03-04	4.99-02	**–3.63-01**	1.73E+01	2.79-01	**1.75E+01**
Iron (Fe)	–2.10-03	–3.81-05	–1.00-06	4.47-05	**–2.89-03**	2.27-02	5.11-03	**2.78-02**
Barium (Ba)	–5.97-04	–1.24-05	–1.46-06	7.53-05	**–1.25-03**	2.63-02	3.88-04	**2.67-02**
Potassium (K)	–2.10-03	–4.05-05	–2.82-06	1.57-04	**–3.64-03**	9.80-03	5.48-03	**1.53-02**
Total Suspended Solids (TSS)	–3.45-03	–1.18-04	–3.94-05	1.65-03	**–1.74-02**	4.86-03	4.96-03	**9.82-03**
Nitrogen (Total N)	–9.01-05	–4.32-06	–2.01-06	9.75-05	**–9.88-04**	6.13-03	3.36-03	**9.50-03**
Total Organic Carbon (TOC)	–1.08-03	–1.04-04	–1.03-05	4.78-03	**–1.75-03**	3.34-03	3.55-03	**6.89-03**
Boron (B)	–9.01-05	–2.43-06	–5.29-07	9.83-06	**–1.90-04**	4.42-03	2.24-03	**6.66-03**
Silica (Si)	–5.94-08	–1.11-09	–2.17-11	4.43-09	**–1.87-05**	4.06-03	2.12-03	**6.18-03**
Aluminum (Al)	–6.52-03	–1.14-04	–5.41-07	8.80-05	**–8.12-03**	3.34-03	2.01-03	**5.35-03**
Magnesium (Mg)	–5.26-03	–9.31-05	–1.21-06	1.13-04	**–6.88-03**	3.68-03	6.06-04	**4.29-03**

Negative values indicate that elimination of an emission by the CCP eliminated an emission from virgin raw material production in the upstream LCI. Materials shown represent the greatest 99.9% of all emissions to land by mass

Table 5C: Complete inventory of emissions to land

	Boiler Slag Beneficial Use			FGD Material Beneficial Use		
Emission (kg)	**Blasting Grit and Roofing Granules**	**Mineral Filler**	**Structural Fill**	**Cement**	**Gypsum**	**Soil Amendment**
Barium (Ba)	–2.62-08	–3.79-07	–1.89-10	–3.65-06	–1.36-05	–2.31-03
Copper (Cu)	–1.61-08	–2.32-07	–1.16-10	–2.23-06	–8.36-06	–1.41-03
Manganese (Mn)	–5.18-09	–7.64-08	–3.74-11	–7.25-07	–7.30-06	–4.54-04
Zinc (Zn)	–4.95-09	–6.62-08	–3.56-11	–6.31-07	–4.38-06	–3.97-04
Chromium (Cr)	–2.78-09	–4.03-08	–2.00-11	–3.87-07	–1.44-06	–2.45-04
Nickel (Ni)	–1.97-09	–2.76-08	–1.42-11	–2.65-07	–1.04-06	–1.68-04
Arsenic (As)	–1.81-09	–2.62-08	–1.30-11	–2.52-07	–9.87-07	–1.59-04
Lead (Pb)	–1.70-09	–2.18-08	–1.22-11	–2.10-07	–9.22-07	–1.32-04
Vanadium (V)	–8.60-10	–1.25-08	–6.20-12	–1.20-07	–4.47-07	–7.58-05
Cobalt (Co)	–2.37-10	–3.31-09	–1.71-12	–3.19-08	–1.25-07	–2.01-05
Mercury (Hg)	–2.08-11	–2.85-10	–1.49-13	–2.73-09	–1.11-08	–1.73-06
Molybdenum (Mo)	–1.26-11	–1.83-10	–9.10-14	–1.76-09	–6.56-09	–1.11-06
Beryllium (Be)	–2.89-12	–4.18-11	–2.08-14	–4.02-10	–1.50-09	–2.54-07

	Fly Ash and Bottom Ash Beneficial Use			Transport	Total	Disposal (50% of CCPs Generated)		
Emission (kg)	**Cement**	**Road Base and Subbase**	**Structural Fill**	**Transport 50 miles**	**Beneficial Use Total**	**Impound-ment**	**Landfill**	**Disposal Total**
Barium (Ba)	–9.47-05	–1.93-06	–4.80-08	1.64-05	**–2.41-03**	2.41-05	8.64E+00	**8.64E+00**
Copper (Cu)	–5.79-05	–1.18-06	–2.94-08	1.00-05	**–1.47-03**	1.48-05	5.29E+00	**5.29E+00**
Manganese (Mn)	–1.88-05	–3.83-07	–9.50-09	3.22-06	**–4.78-04**	4.75-06	1.70E+00	**1.70E+00**
Zinc (Zn)	–1.64-05	–3.35-07	–9.04-09	2.86-06	**–4.16-04**	4.27-06	1.49E+00	**1.49E+00**
Chromium (Cr)	–1.00-05	–2.05-07	–5.09-09	1.74-06	**–2.55-04**	2.56-06	9.17-01	**9.17-01**
Nickel (Ni)	–6.90-06	–1.40-07	–3.61-09	1.20-06	**–1.75-04**	1.77-06	6.28-01	**6.28-01**
Arsenic (As)	–6.55-06	–1.33-07	–3.32-09	1.13-06	**–1.66-04**	1.67-06	5.97-01	**5.97-01**
Lead (Pb)	–5.44-06	–1.11-07	–3.10-09	9.54-07	**–1.38-04**	1.43-06	4.95-01	**4.95-01**
Vanadium (V)	–3.11-06	–6.34-08	–1.58-09	5.38-07	**–7.90-05**	7.92-07	2.84-01	**2.84-01**
Cobalt (Co)	–8.27-07	–1.69-08	–4.34-10	1.44-07	**–2.10-05**	2.13-07	7.54-02	**7.54-02**
Mercury (Hg)	–7.10-08	–1.44-09	–3.80-11	1.24-08	**–1.80-06**	1.84-08	6.47-03	**6.47-03**
Molybdenum (Mo)	–4.56-08	–9.30-10	–2.31-11	7.89-09	**–1.16-06**	1.16-08	4.17-03	**4.17-03**
Beryllium (Be)	–1.04-08	–2.13-10	–5.29-12	1.80-09	**–2.65-07**	2.66-09	9.52-04	**9.52-04**

Negative values indicate that elimination of an emission by the CCP eliminated an emission from virgin raw material production in the upstream LCI. Materials shown represent the greatest 99.9% of all emissions to land by mass